

QUANTITATIVE SPECIES MEASUREMENTS IN MICROGRAVITY COMBUSTION FLAMES

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INTRODUCTION

Flame-vortex interactions are canonical configurations that can be used to study the underlying processes occurring in complicated turbulent reacting flows. The elegant simplicity of the flame-vortex interaction permits the study of these complex interactions under relatively controllable experimental configurations, in contrast to direct measurements in turbulent flames. The ability to measure and model the fundamental phenomena that occur in a turbulent flame, but with time and spatial scales which are amenable to our diagnostics, permits significant improvements in the understanding of turbulent combustion under both normal and reduced gravity conditions.

In this paper, we report absolute mole fraction measurements of methane in a reacting vortex ring. These microgravity experiments are performed in the 2.2-sec drop tower at NASA Glenn Research Center. In collaboration with Drs. Chen and Dahm at the University of Michigan, measured methane absorbances are incorporated into a new model from which the temperature and concentrations of all major gases in the flame can be determined at all positions and times in the development of the vortex ring. This is the first demonstration of the ITAC (Iterative Temperature with Assumed Chemistry) approach, and the results of these computations and analyses are presented in a companion paper by Dahm and Chen [1] at this Workshop. We believe that the ITAC approach will become a powerful tool in understanding a wide variety of combustion flames under both equilibrium and non-equilibrium conditions.

EXPERIMENTAL

Determination of the gas concentrations and temperatures is accomplished by tunable diode laser absorption using 2f wavelength modulation spectroscopy (WMS) [2-3]. With an axisymmetric flame, line-of-sight absorption measurements are inverted [4] to provide radial mole fraction profiles with high spatial and temporal resolution. The new system used in this work is more compact and uses much less power than earlier designs. This accomplishment arises from the use of a digital signal processor (DSP) to control the hardware, acquire and process the data, and then transmit the data to a laptop computer after the drop.

The vortex ring is generated by issuing methane into an air environment through the exit of an axisymmetric nozzle. The experiments are conducted under microgravity conditions in order to remove the undesirable effects of buoyancy that can affect both the flame structure and ring dynamics resulting in possibly asymmetric and non-repeatable interactions [5]. Figure 1 is a photograph of the experiment drop package, showing the vacuum system, vortex generator system,

nozzle/plenum assembly, WMS controller and data acquisition system on the top shelf. The laser absorption system and test section hang below the center of this, where the laser beam scanning region can be adjusted to any distance below the nozzle plane. The power supply for spark generation, power distributor, batteries, B/W CCD camera, and video transmitters reside on the bottom shelf.

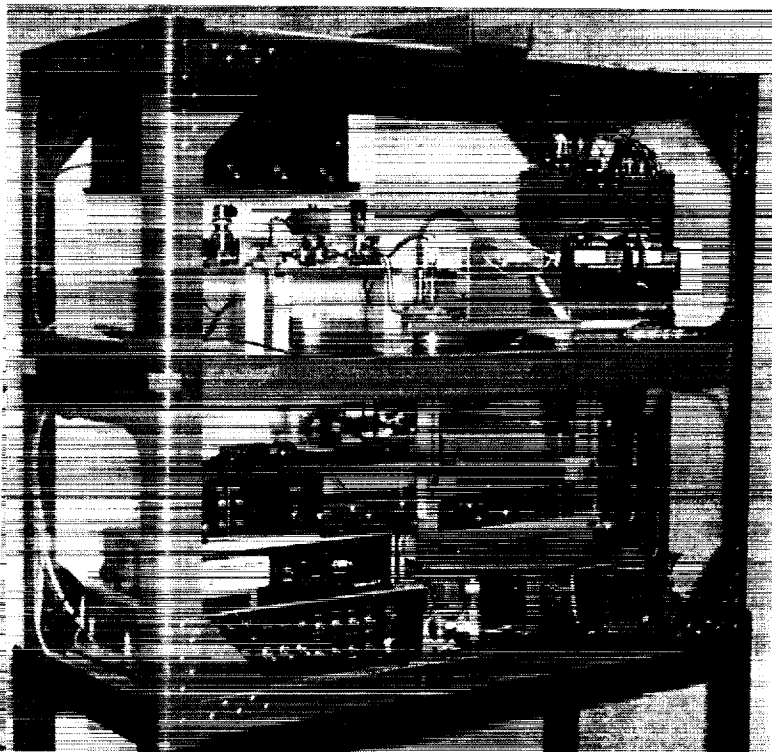


Figure 1 - Experimental drop rig package.

The vortex ring and drop rig have been described in detail previously [6,7]. The ring diameter in these experiments is 2 cm. Since methane is lighter than air, the flame is pointed downward so that the pre-drop mixing with air for proper ignition can be accomplished. The laser DSP system has also been described in a prior publication [8], but in brief, comprises a 1-mm dia. collimated laser beam pointed onto a raster scanner mirror. The center of this mirror is located at the focal point of an off-axis paraboloidal reflector (OAP). As the scanner is rotated over an angle of $\sim 13^\circ$, the laser beam tracks in parallel lines across the flame. A second OAP collects the beam and refocuses it onto an extended-wavelength InGaAs photodiode. The result of this process is that data acquired sequentially in time can be used to obtain spatially-resolved line-of-sight measurements through the flame.

In these experiments, a Sensors Unlimited diode laser is used to detect the nearly degenerate rotational triplet R3 A2 in the $2\nu_3$ vibrational band of methane at 1652.9 nm. Spectroscopic parameters used to analyze these spectra are obtained from the HITRAN database [9]. Each spectrum of 65 points, spanning a 1.38 cm^{-1} wavelength range, are recorded in 3.0 msec. The raster scanner is set up so that the product of spatial steps and scans/second is constant, so that for a scan range of 30 mm at a resolution of 2 mm, a full spatial map is acquired in 51 msec. A number of runs were made with higher spatial resolution (1 mm) over a shorter total range of 16 mm, and higher temporal resolution (25 msec) with a 2 mm spacing over a 16 mm range. These help us to interpolate all of the data to higher resolution.

The DSP board controls all laser and scanner ramps, and acquires the raw data from the photodiode. These data are then $2f$ demodulated at the correct phase, normalized to the incident laser intensity and stored for subsequent download. The vortex ring is ignited approximately 0.5 seconds after the rig is released.

RESULTS

Spatial-temporal maps of methane in the microgravity flame vortex were recorded at heights of 5.0 mm, 12.7 mm and 19.1 mm. Noise and background terms (offsets and optical interference fringes) are removed using a singular valued decomposition (SVD) approach which determines a set of orthogonal basis functions to represent the data where no true absorptions of methane are present (*i.e.*, at times before the vortex ring is released). The actual integrated absorbance of each projection and time is found by a multi-linear least-squares fit of the experimental spectrum to a design matrix comprised of a reference spectrum (0.10 mole fraction methane at 733 Torr and 296 K) and the largest fifteen background basis vectors. An example of filtered spectra at a particular drop time is shown in Fig. 2. The 16 spectra correspond to each of the spatial locations between the center of the flame and 30 mm away at 2 mm increments. Larger absorbances closer to the vortex centerline (0 mm) are observed.

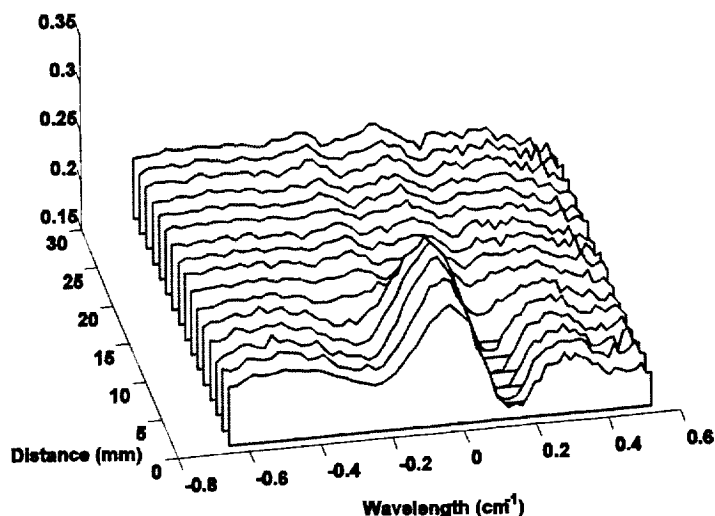


Figure 2 - $2f$ WMS spectra of methane for different distances from flame center at a height of 12.5 mm, 0.75 seconds after the package was released.

The resulting absorbance maps as a function of projection distance are then inverted to radial maps using the Abel inversion routines of Dasch [4]. From the radial absorbances, we then determine absolute mole fractions at each position and time assuming methane is at the reference condition. Contour maps of these results are shown in Fig. 3.

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Collapsing the spectra to a single absorbance before the radial inversion is truly valid only if the $2f$ line shape is independent of temperature and mole fraction. While not strictly true, we can compute correction factors that can be applied to the radial absorbances to accommodate these effects. These correction terms, as well as factors for temperature-dependent cross sections, are applied in the ITAC iterations to produce final temperature and concentration maps. These are presented in the companion paper by Dahm and Chen [1].

DISCUSSION

As confirmed by the video record of the vortex ring, the flame front rapidly expands into its characteristic shape with a diameter of approximately 2 cm. As will be shown [1], the nominal mole fractions observed here will significantly increase to expected levels when the temperature corrections are applied.

Besides our earlier work [8,10], there are no other published results of quantitative species concentration measurements in microgravity combustion. This paper demonstrates that these type

of measurements can provide detailed spatial and temporal information that can be of great assistance toward improving the detailed models and our understanding of combustion phenomena under microgravity conditions. The ITAC method may prove to be a very powerful tool in elucidating the composition of many flames.

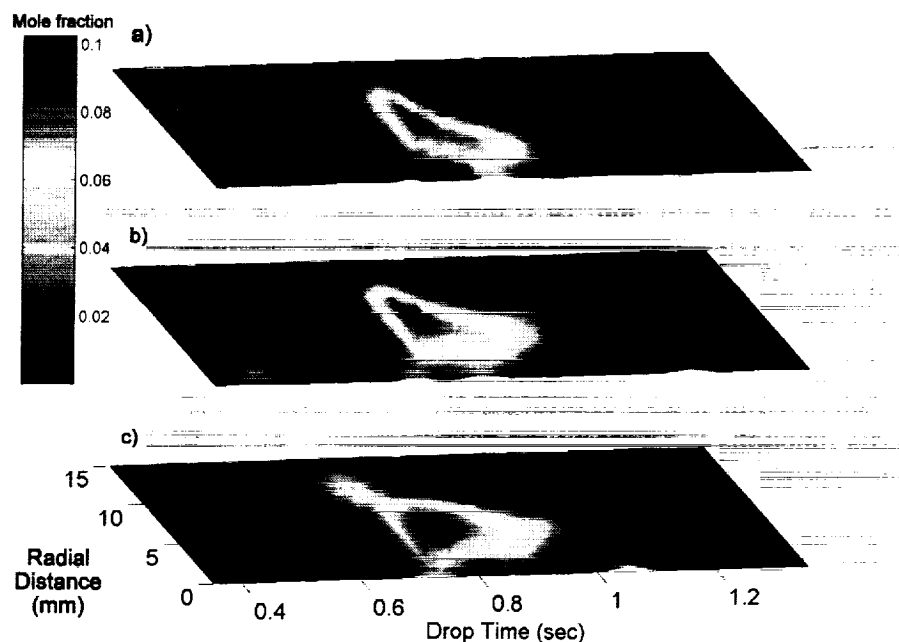


Figure 3 - Contour maps of nominal mole fraction (at reference conditions) at heights of a) 19.1 mm, b) 12.7 mm and c) 5.0 mm from the nozzle plane as a function of drop time and radial distance from the flame center axis.

As part of this effort, we plan to expand these measurements to other gases such as CO_2 or H_2O to fill in the spatial regions where methane has been consumed, as well as measure OH radical mole fractions. Hydroxyl measurements would allow the ITAC method to be expanded to reacting flows where non-equilibrium chemistry effects are important. We also hope to compare these measurements to other combustion system in both normal and reduced gravity.

ACKNOWLEDGMENT

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